Neutrinos from a core collapse supernova [1]

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Abstract. The neutrino burst from a galactic supernova can help determine the neutrino mass hierarchy and θ_{13}, and provide crucial information about supernova astrophysics. Here we review our current understanding of the neutrino burst, flavor conversions of these neutrinos, and model independent signatures of various neutrino mixing scenarios.

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Neutrino flavor conversions inside a SN are sensitive to extremely small θ_{13} values and the nature of neutrino mass hierarchy [1]. The observation of the neutrino burst from a galactic SN will therefore provide information complementary to that from a long baseline experiment. It will shed light on many of the outstanding questions in neutrino oscillation physics and astrophysics.

In this article, we shall follow the production, propagation and detection of SN neutrinos, which are akin to the source, the long baseline and the far detector of a neutrino factory setup.

OPERATION OF THE SN ν-FACTORY

Core collapse and SN explosion

Neutrinos and antineutrinos of all species are produced inside the SN through pair production processes. In addition, ν_e is also produced by electron capture on protons: $pe^- \to n\nu_e$. Before the collapse, neutrinos of all species are trapped inside their respective "neutrinospheres" around $\rho \sim 10^{10}$g/cc.

When the iron core reaches a mass close to its Chandrasekhar limit, it becomes gravitationally unstable and collapses. A hydrodynamic shock is formed when the matter reaches nuclear density and becomes incompressible. When the shock wave passes through the ν_e neutrinosphere, a short ν_e "neutronization" burst is emitted, which lasts for $\sim$10 ms. The object below the shock wave, the "protoneutron star," then cools down with the emission of neutrinos of all species. This emission takes place over a time period of $t \sim 10$ s [2].

The eventual explosion of the star involves the stalling of the original shock wave, its revival by the trapped neutrinos, and a "delayed" explosion where large scale convections play an important role [3, 4]. However, for the ~ 10 sec neutrino burst that we focus on here, the actual explosion mechanism, or even whether the star successfully explodes or not, is mostly immaterial.

The source: primary neutrino fluxes

A SN core acts essentially like a neutrino blackbody source with flavor-dependent fluxes. Since the fluxes are almost identical for $\nu_\mu, \nu_\tau, \bar{\nu}_\mu$ and $\bar{\nu}_\tau$, all these species may be represented by ν_x. The "primary fluxes" $F^0_{\nu_\alpha}$ may be parametrized by the total number fluxes $\Phi_0(\nu_\alpha)$, average energies $\langle E_0(\nu_\alpha)\rangle$, and the "pinching parameters" that characterize their spectral shapes [5].

The values of the parameters are highly model dependent, as can be seen from Table 1. The two leading models – the Livermore simulation [6] and the more recent Garching calculation [7] – agree on $\langle E_0(\nu_e)\rangle \approx 12$ MeV and $\langle E_0(\bar{\nu}_e)\rangle \approx 15$ MeV, and have consistent values for the pinching parameters, but they differ widely on $\langle E_0(\nu_x)\rangle$ and the ratios of total fluxes. In particular, the equipartition of energy assumed in the Livermore model is not a feature of the Garching model.

TABLE 1. Differences in flux predictions from SN models

Model	$\langle E_0(\nu_x)\rangle$	$\frac{\Phi_0(\nu_e)}{\Phi_0(\nu_x)}$	$\frac{\Phi_0(\bar{\nu}_e)}{\Phi_0(\nu_x)}$
Garching	18	0.8	0.8
Livermore	24	2.0	1.6

In the light of the model dependence, it is important to make sure that the inferences drawn from the observed neutrino spectra do not depend strongly on the exact model parameters.

[1] Plenary talk at NuFact07

FLAVOR TRANSFORMATIONS ALONG THE LONG BASELINE

Neutrinos that are produced approximately as mass eigenstates at very high ambient matter density in the core propagate outwards from the neutrinosphere. They have to travel through the core, mantle and envelope of the star, through the interstellar space, and possibly even through some part of the Earth before arriving at the detector. Inside the SN, collective and MSW matter effects take place. In the interstellar space, neutrino mass eigenstates travel independently, whereas oscillations, enhanced by MSW effects, occur inside the Earth.

MSW resonances inside the SN

The traditional picture of flavor conversions in a SN is based on the assumption that the effect of neutrino-neutrino interactions is small. In this case, flavor conversions occur most efficiently in the MSW resonance regions. SN neutrinos must pass through two resonance layers: the H-resonance layer at $\rho_{\rm H} \sim 10^3$ g/cc characterized by $(\Delta m^2_{\rm atm}, \theta_{13})$, and the L-resonance layer at $\rho_{\rm L} \sim 10$ g/cc characterized by $(\Delta m^2_{\odot}, \theta_{12})$. This hierarchy of the resonance densities, along with their relatively small widths, allows the transitions in the two resonance layers to be considered independently [8].

The outcoming incoherent mixture of vacuum mass eigenstates is observed at a detector as a combination of primary fluxes of the three neutrino flavors:

$$F_{\nu_e} = pF^0_{\nu_e} + (1-p)F^0_{\nu_x} \; , \tag{1}$$

$$F_{\bar{\nu}_e} = \overline{p}F^0_{\bar{\nu}_e} + (1-\overline{p})F^0_{\nu_x} \; , \tag{2}$$

where p and $\overline{p}$ are the survival probabilities of ν_e and $\bar{\nu}_e$ respectively.

TABLE 2. Survival probabilities for neutrinos, p, and antineutrinos, $\overline{p}$, in various mixing scenarios

	Hierarchy	$\sin^2\theta_{13}$	p	$\overline{p}$
A	Normal	$\gtrsim 10^{-3}$	0	$\cos^2\theta_\odot$
B	Inverted	$\gtrsim 10^{-3}$	$\sin^2\theta_\odot$	0
C	Any	$\lesssim 10^{-5}$	$\sin^2\theta_\odot$	$\cos^2\theta_\odot$

The neutrino survival probabilities are governed by the adiabaticities of the resonances traversed, which are directly connected to the neutrino mixing scheme. In particular, whereas the L-resonance is always adiabatic and appears only in the neutrino channel, the adiabaticity of the H-resonance depends on the value of θ_{13}, and the resonance shows up in the neutrino (antineutrino) channel for a normal (inverted) mass hierarchy. Table 2 shows the survival probabilities in various mixing scenarios. For intermediate values of θ_{13}, i.e. $10^{-5} \lesssim \sin^2\theta_{13} \lesssim 10^{-3}$, the survival probabilities depend on energy as well as the details of the SN density profile [1].

Scenarios A, B and C are the ones that can in principle be distinguished through the observation of a SN neutrino burst. Note that the sensitivity to θ_{13} is comparable to the expected reach of a neutrino factory.

Collective effects at large ν densities

The neutrino and antineutrino densities near the neutrinosphere are extremely high (10^{30-35} per cm^3), which make the $\nu-\nu$ interactions in this region significant [9, 10]. Indeed, the Hamiltonian is now given by

$$H(\mathbf{p},\mathbf{r}) = H_{vac}(p) + V(\mathbf{r}) + H_{\nu\nu}(\mathbf{p},\mathbf{r}) \; , \tag{3}$$

where H_{vac} is the vacuum Hamiltonian, $V(\mathbf{r})$ is the MSW potential due to electrons and the $\nu-\nu$ interaction potential $H_{\nu\nu}$ is [11, 12, 13]

$$H_{\nu\nu}(\mathbf{p},\mathbf{r}) = \sqrt{2}G_F \int \frac{d^3\mathbf{q}}{(2\pi)^3} \kappa_{\mathbf{pq}} (n_\nu \rho - \bar{n}_\nu \bar{\rho}) \; . \tag{4}$$

Here $n_\nu(\mathbf{q},\mathbf{r},t)$ and $\rho(\mathbf{q},\mathbf{r},t)$ are the number density and density matrix of neutrinos with momentum $\mathbf{q}$, whereas $\kappa_{\mathbf{pq}} \equiv (1-\cos\theta_{\mathbf{pq}})$. The quantities with a "bar" represent antineutrinos. Note that the evolutions for ν and $\bar{\nu}$ are nonlinear, and are coupled to each other.

The distinctive features in the flavor evolution of such a relativistic gas have been identified in [14, 15, 16, 17]. The evolutions of the density matrices of neutrinos and antineutrinos may be represented in terms of the precessions of the corresponding Bloch vectors, termed as "polarization vectors" $\mathbf{P}$. The traditional MSW oscillations correspond to ν and $\bar{\nu}$ of each energy independently precessing about $\mathbf{B}$, the Bloch vector corresponding to the Hamiltonian $H_{vac}(p)+V(\mathbf{r})$.

Different collective effects play important roles in different regions of the star [18]. When the neutrino density is extremely high, $\mathbf{P}$'s of all energies remain tightly bound together and precess with a common frequency, giving rise to synchronized oscillations [19]. At lower densities, the $\mathbf{P}$'s remain bound together to a large extent, but have a tendency to relax to the state that has the lowest energy, causing bipolar oscillations [20, 21]. Collective interactions also predict "spectral split," a complete swapping of the energy spectra of two neutrino flavors above or below a critical energy, as the neutrinos transit from a region where collective effects dominate to a region where the neutrino density is low [22, 23].

The analytic treatment of collective effects till now has been mostly in the two-flavor limit, assuming a steady-state, spherical, half-isotropic, finite source. The dependence of the flavor evolution on the direction of

propagation of the neutrino may give rise to direction-dependent evolution [9, 10], or to decoherence effects [16, 24], but for a realistic asymmetry between neutrino and antineutrino fluxes, such effects are likely to be small [18, 25] and a so-called "single-angle" approximation can be used. Recently, a formalism for analyzing the three-flavor effects has also been developed [26].

For SN density profiles where the collective effects are over before the MSW effects begin, the collective effects are equivalent to changing the primary spectra available for further propagation, so that results in Table 2 stay valid. For "shallow" density profiles [27] where the collective and MSW regions may overlap, the situation is more complex and has to be analyzed separately.

Oscillations inside the Earth matter

If the neutrinos travel through the mantle, and possibly core, of the Earth before reaching the detector, the neutrinos undergo oscillations inside the Earth and the survival probabilities change [28, 29, 30]. This change however occurs only in those scenarios in Table 2 where the value of the survival probability is nonzero. This provides the means for discriminating between various mixing scenarios.

When antineutrinos, for example, travel through the mantle and the core of the earth, the sharp density jumps give rise to the survival probability of the form [31]

$$\bar{p}^D \approx \cos^2\theta_{12} + \sum_{i=1}^{7} \bar{A}_i \sin^2(\phi_i/2) \tag{5}$$

in the two-layer model of the Earth, where the coefficients $\bar{A}_i$ are functions of the mixing angle θ_{12} in vacuum, mantle and core. The phases ϕ_i depend on the distance L traveled through the Earth matter and the values of mass squared differences $\overline{\Delta m^2}$ between $\bar{\nu}_1$ and $\bar{\nu}_2$ in the mantle and the core. If the neutrinos traverse only through the mantle, only one oscillating term is present in (5), with $\phi = 2\overline{\Delta m^2}_{\rm mantle} L/E$ [32].

DISTINGUISHING BETWEEN NEUTRINO MIXING SCENARIOS

The only SN observed in neutrinos till now, SN1987A, yielded only $\sim$20 events. Though it confirmed our understanding of the SN cooling mechanism, the number of events was too small to say anything concrete about neutrino mixing (see [33] and references therein). On the other hand, If a SN explodes in our galaxy at 10 kpc from the Earth, we expect $\sim 10^4$ events at Super-Kamiokande (SK) through the inverse beta decay process $\bar{\nu}_e p \to n e^+$. This process, dominant at any water Cherenkov or scintillation detector, will be instrumental in determining the $\bar{\nu}_e$ spectrum. In order to measure the ν_e spectrum cleanly, however, one needs a large liquid Ar detector, with the relevant process $\nu_e + {}^{40}\text{Ar} \to {}^{40}\text{K}^* + e^-$.

The uncertainties in the primary neutrino spectra make the task of determining the survival probabilities p and $\bar{p}$ almost impossible, and alternative model independent signatures of various neutrino mixing scenarios need to be looked for. The Earth effects and shock wave imprints seem particularly promising for this purpose. Since the characteristics of the neutronization burst are robust across models, the structure of the neutronization peak can also identify scenario A, where the peak is highly suppressed [34].

Earth effects manifest themselves in two ways. Firstly, the total number of events and the spectral shape changes. Secondly, Earth effect oscillations are introduced, which may be identified even at a single detector.

Comparing signals at multiple detectors

If neutrinos travel different distances through the Earth before reaching two detectors, the difference in the signals at the detectors could show evidence for Earth effects. In order to obtain a statistically significant difference in the neutrino spectra, the detectors need to be of the size of SK or larger.

The IceCube detector, though designed to detect individual neutrinos with $E \gtrsim 150$ GeV, is able to detect a SN neutrino burst during which the number of Cherenkov photons detected by the optical modules would increase much beyond the background fluctuations [35, 36]. Though this does not measure energies of individual neutrinos, the total luminosity can be determined at the per cent level. Comparison of the luminosities as functions of time at the IceCube and SK (or its larger version) can identify the earth effects, since they are typically time dependent [37].

The relative locations of SK and IceCube imply that for the SN in a large portion of the sky, neutrinos pass through the Earth for only one of the detectors. This makes the SK–IceCube comparison an interesting prospect.

Identifying Earth effects at a single detector

The oscillating terms $\sin^2(\phi_i/2)$ in (5) can manifest themselves as peaks in the Fourier power spectrum of the "inverse energy" spectrum of $\bar{\nu}_e$ [32]:

$$G_N(k) = \left| \sum_{\rm events} e^{iky_{\rm event}} \right|^2 / N_{\rm events} \ , \tag{6}$$

where $y \equiv (25\,\text{MeV})/E$. The positions of these peaks are independent of the primary neutrino spectra, being determined by the solar oscillation parameters, the Earth matter density, and the position of the SN in the sky. Therefore, Earth effects can be identified merely by identifying the presence of these oscillation frequencies in the observed spectrum. If the neutrinos pass only through the mantle, there is only one Fourier peak. When the core is also involved, three out of the seven possible peaks may have significant power [31], leading to an easier identification of the Earth matter effects.

Finite energy resolutions of detectors tend to smear out the modulations in the energy spectrum, and suppress high-k peaks. The comparison between a simulated megaton water Cherenkov detector and a 32 kt scintillation detector [31] shows that the better resolution of the scintillator detector almost compensates for the much larger water Cherenkov detector size.

The observation of Earth effects in ν_e $(\bar{\nu}_e)$, either through the luminosity comparison or through Fourier peaks, eliminates scenario A (B) independently of SN models.

NEUTRINOS FOR SN ASTROPHYSICS

Pointing to the SN in advance

Since neutrinos are expected to arrive hours before the optical signal from the SN, the neutrino burst serves as an early warning [38] to the astronomy community. Being able to determine the position of the SN in the sky is also crucial for determining the Earth crossing path for the neutrinos in the absence of the SN observation in the electromagnetic spectrum.

A SN may be located through the directionality of the $\nu e^- \to \nu e^-$ elastic scattering events in a water Cherenkov detector such as SK [39, 40]. The directionality of this reaction is primarily limited by the angular resolution of the detector, the kinematical deviation of the final-state electron direction from the initial neutrino, and the nearly isotropic $\bar{\nu}_e p \to n e^+$ background which is 30-40 times larger than the signal. Adding to the water a small amount of gadolinium, an efficient neutron absorber, would allow one to detect the neutrons and thus to tag the inverse beta reactions [41]. Efficient neutron tagging can improve the pointing accuracy at SK from $\sim 8^\circ$ to $\sim 3^\circ$ for a SN at 10 kpc [42].

Tracking the shock wave in neutrinos

The passage of the shock wave through the H-resonance ($\rho \sim 10^3$ g/cc) a few seconds after the core bounce may break adiabaticity, thereby modifying the spectral features of the observable neutrino flux [43, 44, 45, 46]. One expects a "dip" in $\langle E_e \rangle$ as well as the number of events, and a simultaneous peak in $\langle E_e^2 \rangle / \langle E_e \rangle^2$. If a reverse shock is also present, the above features become a a double-dip and a double-peak respectively [47].

Since the density of the H-resonance layer depends on energy, the positions of the dips in the number of events at different neutrino energies would allow one to trace the shock propagation while it is in the mantle around densities of $\rho \sim 10^3$ g/cc [47].

The shock wave effects can be diluted by stochastic density fluctuations as well as turbulence. For example, for $\theta_{13} \gtrsim 10^{-4}$ the shock wave imprints may be partly erased with δ-correlated stochastic fluctuations [48]. If the turbulent convection generated behind the shock wave is sufficiently large, flavor depolarization takes place at the H resonance, so that the sharp shock wave effects are replaced by gradual depolarization effects [49]. A recent hydrodynamic simulation [50] suggests that some of the shock wave effects survive in spite of the smearing factors above. Sterile neutrinos may leave their imprints in the shock wave [51], which can also survive in the presence of turbulence [52].

The nonmonotonic density profile of the shock wave may cause the neutrinos to pass through multiple H resonances. This gives rise to oscillations in the survival probabilities of neutrinos, where the positions of maxima and minima are independent of primary fluxes [53]. The oscillations are however smeared out due to the finite energy resolutions of detectors, and the signal may be detectable only in extremely optimistic cases.

The observation of any of the shock wave imprints in the ν_e $(\bar{\nu}_e)$ spectra would imply that the neutrino mixing scenario is A (B).

SYNERGY BETWEEN SN NEUTRINOS AND A NEUTRINO FACTORY

A galactic SN burst is a rare phenomenon, expected to occur only once in a few decades. However, its observation is expected to reap a rich scientific harvest. It is therefore imperative that we are ready with suitable long term detectors that will observe the relevant signals. In the meanwhile, better theoretical understanding of neutrino transport inside the SN, combined with more accurate measurements of the neutrino mixing parameters, will equip us for making the most of the cosmic catastrophe.

Earth effects and shock wave imprints are robust signals for specific neutrino mixing scenarios that are unlikely to be mimicked by anything else. The information available from them is in the form of a combination of

mass hierarchy and a θ_{13} range, so that complementary information from long baseline experiments is also required. If θ_{13} and mass hierarchy is already determined at terrestrial experiments, concrete information on the primary neutrino fluxes will be obtained. On the other hand, if the burst is observed before the mixing parameters are measured, we shall have some advance idea about the neutrino mixing parameters expected, and that will guide our efforts towards the neutrino factory.

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